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A Comparative Review on Bisphenol A Sources, Environmental Levels, Migration, and Health Impacts in India and Global Context

Sugata Datta*(***), Abhishek Chauhan†, Anuj Ranjan**(********), Abul Hasan Sardar***, Hardeep Singh Tuli****, Seema Ramniwas*****, Moyad Shahwan******(*******), Ujjawal Sharma********* and Tanu Jindal****

*Amity Institute of Environmental Sciences, Amity University, Noida Campus, U.P., India
**Amity Institute of Environmental Toxicology Safety and Management, Amity University, Noida, U.P., India
***University of Calcutta, West Bengal, India
****Department of Biotechnology, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala 12 133207, Haryana, India
*****University Centre for Research & Development, University Institute of Pharmaceutical Sciences, Chandigarh University, Gharuan, Mohali, Punjab, India
******Department of Clinical Sciences, College of Pharmacy and Health Sciences, Ajman University, Ajman 346, UAE
*******Centre of Medical and Bio-Allied Health Sciences Research, Ajman University, Ajman 346, UAE
********Academy of Biology and Biotechnology, Southern Federal University, Rostov-On-Don, Russia
*********Department of Human Genetics and Molecular Medicine, School of Health Sciences, Central University of Punjab, Bathinda, India
†Correspondence author: Abhishek Chauhan; akchauhan@amity.edu

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ABSTRACT

Bisphenol A (BPA) is a widely utilized chemical found in numerous everyday products, including plastic containers, food packaging, and thermal paper. Research has linked BPA exposure to a range of health concerns, encompassing developmental and reproductive issues, cancer, and obesity. Given India's status as one of the world's largest producers and consumers of plastic goods, understanding the potential risks associated with BPA exposure and its health impacts on the Indian population is of paramount importance. This paper conducts a comparative analysis of BPA sources, environmental levels, migration, and health impacts in India in comparison to other countries. By examining data from various nations, we aim to discern overarching trends and patterns in BPA exposure and its associated health effects. This analysis serves as a foundation for the development of policies and regulations designed to safeguard public health. While the Indian government has taken some regulatory steps, such as banning the production, import, and sale of BPA-containing polycarbonate baby bottles, there is a notable absence of specific regulations or bans on BPA in other food-contact materials (FCMs). Studies conducted in India have detected BPA in various food items, underscoring the potential risk of BPA exposure through food consumption. This emphasizes the urgent need for effective monitoring and control of BPA migration in FCMs within India. In conclusion, this comparative review underscores the imperative for ongoing research and rigorous monitoring of BPA exposure and its health impacts in India, as well as in other nations. Safeguarding the health of the general public necessitates a comprehensive understanding of BPA's prevalence, sources, and consequences. By implementing and refining regulations, such as extending bans on BPA in additional FCMs, policymakers can work towards mitigating the risks associated with BPA exposure and ensuring the safety of populations worldwide.

INTRODUCTION

Bisphenol A (BPA) is a carbon-based synthetic compound that belongs to the two hydroxyphenyl groups of diphenylmethane derivatives and has the chemical formula $C_{15}H_{16}O_2$ and a molecular mass of 228.29 $g.mol^{-1}$. It is an important industrial chemical and is primarily used as an intermediate in the production of polycarbonate (PC) plastics and epoxy resins. BPA and its derivatives such as bisphenol S (BPS), bisphenol F (BPF), bisphenol E (BPE), bisphenol B (BPB), bisphenol Z (BPZ) and bisphenol AF (BPAF) might be released by the imperfect polymerization of the plastic substances that appears during processing or depolymerization due to deliberate heating for sterilization or accidental purposes during storage (Lopes-Rocha et al. 2021).

The European Chemical Agency (ECHA) has added BPA to the list of chemicals of very high concern due to its toxicity, and many regulatory authorities have established specific limits on its usage and migration. The World Health Organization (WHO) convened an expert panel and determined that public limits on BPA are premature (World Health Organization 2009). The US Food and Drug Administration (FDA) issued a report highlighting the potential hazards of BPA. Subsequently, it withdrew approval for the use of BPA-based plastics in packaging materials for baby formula or feeding bottles (US FDA 2014). The European Union (EU) and Canada have implemented similar restrictions. The US Environmental Protection Agency (USEPA) has determined that the toxic level of BPA is as high as 50 $\mu g.kg^{-1}$ of body weight per day, but lower amounts may not be completely safe (European Union 2014). The European Commission (EC) has established a Specific Migration Limit (SML) for BPA in foods of 0.6 $\mu g.g^{-1}$ of the food substance. In 2010, the Indian government prohibited the manufacture, import, and sale of polycarbonate baby bottles containing BPA, citing concerns about its potential health effects on infants. However, there are no specific regulations or bans on the use of BPA in other food-contact materials (FCMs), such as epoxy resins and polystyrene containers. In 2018, the Food Safety and Standards Authority of India (FSSAI) proposed a draft notification to regulate the use of di-(2-ethylhexyl) phthalate (DEHP) in plastic food packaging materials, which included a maximum limit of 1.5 $mg.kg^{-1}$ (FSSAI 2022). The draft notification, however, fails to address the issue of BPA migration from food-contact materials, as it does not make any explicit mention of this concern.

There have been several studies conducted in India that report the migration of BPA from FCMs into food products (Dey 2021, Kumar 2023). These studies have detected BPA in various food items, including canned foods and beverages, baby feeding bottles, and plastic containers used for food storage and microwaving. The levels of BPA migration have been found to vary widely, with some samples containing levels above the regulatory limits set by the authorities. These findings highlight the potential risk of BPA exposure to human health through food consumption and the urgent need for effective monitoring and control of BPA migration in FCMs in India. However, the extent of exposure and associated health risks is still a matter of ongoing research and debate.

Therefore, the purpose of the study holds significant importance for several reasons, as BPA is a widely utilized chemical that is present in several products, such as plastic containers, food packaging, and thermal paper. The chemical can contaminate the environment by leaching out from these products, thereby resulting in potential health hazards. This has led to growing apprehensions about the likely health impacts of BPA exposure, particularly in vulnerable populations such as pregnant women and children. As India is one of the biggest producers and consumers of plastic products worldwide, with a rapidly growing population and economy, India is expected to experience higher levels of BPA exposure in the future. This comparative review can aid in identifying potential sources of exposure, evaluating the present levels of BPA in the environment, and analyzing the health consequences of BPA exposure in various populations. Through a comparison of data from different countries, researchers can also identify trends and patterns in BPA exposure and its health impacts. This information can help in formulating policies and regulations and is crucial in comprehending the potential risks of BPA exposure, identifying exposure sources, and formulating policies and regulations to safeguard public health.

Major Sources of BPA

BPA is predominantly used in the production of polycarbonate and epoxy resins, accounting for 95% of its industrial use (Hahladakis et al. 2023). The remaining 5% is allocated to a diverse range of applications such as phenoplast resins, phenolic resins, unsaturated polyester resins, can linings, antioxidants, PVC manufacturing and processing additives, ethoxylated BPA, dye developer for thermal paper, polyols, modified polyamide, compounding ingredient for car tires, flame retardants (such as tetrabromo BPA), automotive and transportation equipment, optical media (e.g., DVDs), electronic equipment, construction, linings inside drinking water pipes, thermal and carbonless paper coatings, and foundry casting (Huang et al. 2012). BPA is preferred for its use in the manufacturing of polycarbonate plastics due to its capability to produce durable and rigid plastic materials that exhibit resistance to shattering when exposed to temperature variations, be it heat or cold (Dey et al. 2023). BPA is not only cost-effective but also highly efficient, which accounts for its extensive application in the production of various plastic products, particularly those intended for food and beverage containment. Furthermore, BPA's chemical composition includes phenolic epoxy resins, which find application in the creation of protective coatings for food and beverage containers (Sharma et al. 2023). These coatings play a crucial role in safeguarding the contents of the containers by protecting environmental factors like moisture, heat, and bacteria, ensuring the integrity and safety of the stored food and beverages.

BPA Detected in the Environment

BPA has been detected in the environment, including in air, water, soil, and sediment. It can enter the environment through various sources, such as industrial discharge, landfill leachate, and wastewater treatment plant effluent (Wojnowska-Baryła et al. 2022). BPA has also been found in aquatic organisms, which can accumulate in their tissues through food chain transfer (Kataria et al. 2022). The presence of BPA in the environment is a concern due to its potential adverse effects on human health and the ecosystem. Research is ongoing to better understand the sources, fate, and effects of BPA in the environment and to develop strategies to reduce its environmental impact.

Aquatic Environment: BPA is detected in the aquatic environment (both freshwater and marine waters) due to leaching from BPA-based products and also through effluent from wastewater treatment plants and landfill sites. A large number of peer-reviewed studies have reported specific occurrences and concentrations of BPA in aquatic systems. Table 1 lists BPA levels detected in the rivers in different parts of India. The majority of studies conducted showed that the concentrations of BPA detected in the River Ganga were higher than in the rivers of South India (Mukhopadhyay 2020, Gopal 2021). Compared to riverine locations, coastal waters recorded significantly lower BPA levels, as 49 percent of untreated wastewater from the adjacent districts is directly discharged into the riverine region (Yamazaki 2015, Mukhopadhyay 2020). Freshwater discharge during the monsoon period dilutes BPA and the plasticizers. Hence lower concentration is reported (Gopal et al. 2021). The concentration of BPA in the upstream section of the Yamuna River (576-603 $ng.L^{-1}$) was found to be significantly lower than that in the midstream section (10,500-14,800 $ng.L^{-1}$) (Lalwani et al. 2020). This disparity is likely attributed to the convergence of the Najafgarh drain and 14 other drains located between the Wazirabad barrage and Okhla barrage, which are known to discharge untreated sewage, industrial waste, and other pollutants into the river. The contamination of Vembanad Lake in Kerala by untreated effluents from various sources, including agriculture, domestic, municipal, and industrial sectors, has led to the presence of high levels of iron (11.29 ± 0.39 ppm) and BPA (0.02412 ± 0.0031 $\mu g.mL^{-1}$) in the hepatic tissue of edible fish species, particularly *Etroplussuratensis*. The elevated levels of these contaminants have increased hepatic stress markers and distorted hepatic structure in the fish. As a result, consuming contaminated fish from Vembanad Lake is a serious health concern, and effective measures must be taken to mitigate the environmental and health risks associated with pollution in the lake (Pettamanna et al. 2020).

Soil and Sediments: The contamination of sediments in India is largely attributed to the direct discharge of untreated wastewater into rivers, where around 64 percent of the generated wastewater is left untreated. This contamination is further compounded by the disposal of electronic waste, the burning of waste, wastewater discharge, and industrial pollution, which have led to the presence of phthalate esters

Table 1: Concentration of BPA ($ng.L^{-1}$) in aquatic environment in India.

States/Uts	Location	BPA levels {$ng.L^{-1}$]	References
Tamil Nadu	River Kaveri, River Vellar River Tamiraparani	6.6-136 2.8-6 9.8-36	(Kumar et al. 2014)
Uttarakhand, Uttar Pradesh	Entire stretch of River Ganga	140-4460	(Chakraborty et al. 2021)
West Bengal	Wetlands of Sunderbans	210-2820	
Karnataka	River Arkavathi, a tributary of River Kaveri	49.7 (pre-monsoon) 37.6 (post-monsoon)	(Gopal et al. 2021)
West Bengal	River Hooghly	803 (riverine region) 137.4 (estuarine region)	(Mukhopadhyay et al. 2020)
Tamil Nadu	River Cooum Puzhal Lake River Adyar Buckingham Canal Korttalaiyar Canal	264-628 ND 54-512 835-1950 33	(Yamazaki et al. 2015)
Delhi Tamil Nadu	River Yamuna River Cooum	79.6-14,800 1,420	(Lalwani et al. 2020)
Kerala	Lake Vembanad	24,120-31,000 (hepatic tissues of edible fish *Etroplussuratensis*)	(Pettamanna et al. 2020)

ND. Not Detected

(PAEs) and BPA in the soil (Mukhopadhyay et al. 2020). Wastewater discharge from industries and homes, as well as the flow dynamics of rivers, has also been identified as principal sources of BPA in surface riverine sediments in the lower stretch of the River Ganga (Mukhopadhyay & Chakraborty 2021). Estuarine sediments from Mumbai showed the presence of BPA within the range of 16.3-35.79 $\mu g.kg^{-1}$ (Tiwari et al. 2016). Reports have shown similar findings in Zhejiang, China, where farmlands contained BPA, BPF, and BPP (bisphenol P) up to 166, 212.9, and 78.2 $ng.g^{-1}$ dry weight, respectively (Xu et al. 2021). Additionally, landfill leachate in South China showed a total bisphenol content of 32,130 ng/L (Huang et al. 2021). Activated sludge digesters in Shenzhen, China, had BPA concentrations averaging 199.5 $ng.g^{-1}$ dry weight of sludge, suggesting that BPA is the most widely used bisphenol in suspended solids (Qian et al. 2021). BPA concentrations ranging from 82.4-989 $ng.g^{-1}$ of microplastic were found on Hong Kong beaches due to sewage treatment plant discharge (Lo et al. 2021).

ENVIRONMENTAL IMPLICATIONS OF BPA

The widespread use of BPA in various commercial plastic products has resulted in air, water, and soil becoming potential routes of exposure to this compound. Workers involved in the production of epoxy resin-coated metallic cans, PVC films, and thermal paper are at higher risk of BPA exposure. Furthermore, the plastic industry and thermal paper recycling have led to high levels of BPA leaching into the environment, contaminating soil, air, and aquatic environments (Ramakrishna et al. 2021). Uncontrolled residential trash burning in open bins can produce BPA concentrations and emission rates of up to 58.3 $mg.L^{-1}$ and 9.7 $mg.kg^{-1}$, respectively (Vasiljevic & Harner 2021). Therefore, it is apparent that anthropogenic sources are the primary contributors to the presence of BPA in the environment.

Plastic pollution in rivers and oceans is a major environmental hazard. Bisphenols, phthalates, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) are among the most prevalent contaminants detected in plastics that pollute the aquatic environment. With a high detection rate and concentration, BPA is the most prominent bisphenol analog in wastewater treatment plants, followed by BPS and BPF. The adsorption of BPA on primary and activated sludge in the water treatment process results in higher levels of BPA in anaerobically digested sewage

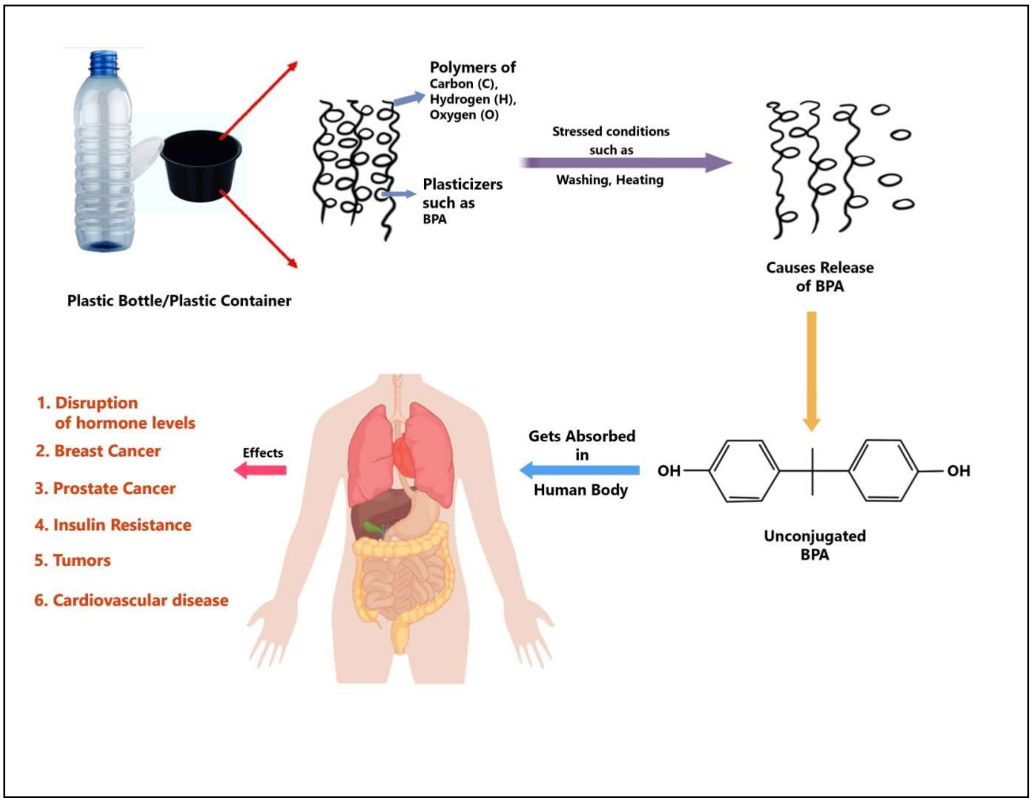

Fig. 1: Mechanism of BPA migration from FCMs and its potential health consequences in humans.

Table 2: BPA leached from FCMs as reported in major countries.

In baby foods				
Location	Food types	BPA content	Types of food containers	References
India	Baby mashed fruit pulp	7.87-61.3 ng.mL^{-1}	PC baby feeding bottles	(Nepalia et al. 2018)
	Baby cereal rice powder			
	Paper-packaged formula milk			
	Formula milk	1.65-7.98 ng.mL^{-1}	Canned	
	Milk	19 ng.mL^{-1}	PC baby feeding bottles	(Shrinithivihahshini et al. 2014)
	Powdered infant milk formula	5.46 ng.g^{-1}	Canned	(Karsauliya et al. 2021)
Egypt	Infant milk formula	87.34-90.95 ng.g^{-1}	Canned	(Osman et al. 2018)
	Milk	69.83-125.66 ng.g^{-1}	PC baby feeding bottles	
Spain	Liquid milk	0.38-547 ng.mL^{-1}	Plastic packaged	(Molina-García et al. 2012)
	Liquid infant formula milk	1.26-6.31 ng.mL^{-1}		
	Solid infant formula or powdered milk	ND		
	Infant formula milk	11-12 ng.g^{-1}	PC baby bottles	(Santillana et al. 2011)
In other foods				
India	Vegetables and fruits	20-440 ng.g^{-1}	Canned	(Chauhan & Jindal 2020)
Spain	Meat products	20 ng.g^{-1}	Canned	(González et al. 2020)
	Fish products	30-40 ng.g^{-1}	Canned	
	Vegetables and fruits	7-90 ng.g^{-1}	Canned	
Egypt	Meat products	31.02- 724.06 ng.g^{-1}	Canned	(Osman et al. 2018)
	Fish products	57.68-168.52 ng.g^{-1}	Canned	
	Vegetables and fruits	7.24-168.59 ng.g^{-1}	Canned	
	Dairy products	32.71-90.95 ng.g^{-1}	Canned	
	Beverages	13.96-14.87 ng.g^{-1}	Canned	
Italy	Beer	0.50-0.80 ng.mL^{-1}	Canned	(Cirillo et al. 2019)
	Tuna	5-120 ng.g^{-1}	Canned	(Fattore et al. 2015)
Southwest	Meat products	ND	Unpackaged (raw)	(Adeyi & Babalola 2019)
Nigeria		21.3 ng.g^{-1}	Canned beef	
	Fish products	0.78 ng.g^{-1}	Unpackaged (raw	
		26.3 ng.g^{-1}	frozen)	
	Dairy products	ND	Canned fish	
		4.8 ng.g^{-1}	Unpackaged	
			Canned milk	
	Vegetables & fruits	ND		
			Raw fruits and	
		0.20 ng.g^{-1}	vegetables	
		1.11 ng.g^{-1}	Canned vegetables	
			Canned fruits	
United	Beverages	0.235 ng.g^{-1}	Canned	(Liao & Kannan 2013)
States	Dairy products	2.55 ng.g^{-1}	Canned	
	Fats and oils	1.90 ng.g^{-1}	Canned	
	Fish and Seafood	3.23 ng.g^{-1}	Canned	
	Cereals	0.605 ng.g^{-1}	Canned	
	Meat and meat products	0.852 ng.g^{-1}	Canned	
	Vegetables	8.99 ng.g^{-1}	Canned	
	Fruits	0.532 ng.g^{-1}	Canned	
Greece	Beverages (soft drinks)	0.4-10.2 ng/mL^{-1}	Plastic	(Tzatzarakis et al. 2017)
		ND	Tetra pack	
	Meat products	<0.6 ng.g^{-1}	Canned	
		<0.6 ng.g^{-1}	Plastic	
	Fish and Seafood	17.2-30.7 ng.g^{-1}	Canned	
	Vegetables	48.3-66 ng.g^{-1}	Canned	
China	Meat products	100-300 ng.g^{-1}	Canned	(Cao et al. 2021)
	Seafood	ND-144 ng.g^{-1}	Canned	
	Fruit	ND-837 ng.g^{-1}	Canned	
	Vegetables	ND-102 ng.g^{-1}	Canned	
	Beverages	2-88 ng.g^{-1}	Canned	
Korea	Meat products	29.57 ng.g^{-1}	Canned	(Choi et al. 2018)
	Fish products	33.43 ng.g^{-1}	Canned	
	Fruits	10.46 ng.g^{-1}	Canned	
	Vegetables	4.67 ng.g^{-1}	Canned	
	Beverages	3.79 ng.g^{-1}	Canned	

ND. Not Detected

sludge. BPA thus accumulates and translocates in agricultural soils after being supplemented with sewage sludge(Hu et al. 2019).BPA leaching or percolation into groundwater from agricultural soils poses a risk to the ecosystem and human health (Mg & Girigoswami 2021). BPA is used as a developing dye for thermal papers; when recycled into toilet paper is transferred to the recycled product and ends up in sewage, where it is partially eliminated during the wastewater treatment process (Hardegen et al. 2021). It has been established that wastewater sludge contains far more BPA than wastewater, and BPA concentrations in sediments in Asia are significantly higher than in Europe and North America (Corrales et al. 2015). The widespread presence of BPA in various environmental media, coupled with its potential adverse effects on human health and ecological systems, underscores the urgency for policymakers and environmental agencies to take prompt and effective measures to mitigate the environmental implications of BPA.

BPA LEACHING FROM FOOD-CONTACT MATERIALS (FCMS)

BPA exposure primarily occurs through dietary intake of food and beverages that have come into contact with these materials (Siddique et al. 2021). Packaged foods have been found to contain the highest levels of BPA, leading to a lowered tolerable daily intake (TDI) by the European Food Safety Agency (EFSA) from 50 to 4 $\mu g.kg^{-1}$ $bw.day^{-1}$ (Opinion et al. 2015). BPA, which is incorporated into plastic containers and used in epoxy resin-coated metal cans to improve their durability and protective properties, has the potential to migrate into food and beverages in specific circumstances. These conditions include exposure to heat, repeated washing, or contact with acidic substances (Fig. 1). The prevalence of BPA exposure and its potential health risks make it a significant public health concern, and measures to reduce exposure through dietary sources and regulate its use in FCMs are necessary to mitigate the risk.

Multiple research investigations have revealed that there is a significant rate of BPA migration from FCMs despite the presence of strict regulations (Table 2). These findings highlight the need for continued monitoring and regulation of FCMs to minimize potential health risks associated with BPA.

BPA REGULATION IN MAJOR COUNTRIES

In the European Union, the European Food Safety Authority (EFSA) established a temporary tolerable daily intake (TDI) of 4 $\mu g.kg^{-1}$ $bw.day^{-1}$ in risk evaluation of BPA. However, in a re-evaluation of BPA's risk assessment, the EFSA's Panel on Food Contact Materials, Enzymes, and Processing Aids (CEP) recommended a significantly lower TDI of 0.04 $ng.kg^{-1}$ $bw.day^{-1}$. This change was based on scientific studies published between 2013 and 2018 that demonstrated the hazardous effects of BPA, including its ability to impact estrogen receptors and alter immune responses. The EFSA suggested this reduction due to the widespread usage of BPA-based products, as all age groups were found to exceed the previous TDI of 4 $\mu g.kg^{-1}$ $bw.day^{-1}$ (Aids 2015).

In the United States, the FDA has calculated estimated daily BPA exposure from its use in FCMs to be 2.42 $\mu g.kg^{-1}$ $bw.day^{-1}$ for infants and 0.185 $\mu g.kg^{-1}$ $bw.day^{-1}$ for adults. To put this into perspective, the FDA has established a No-Observed-Adverse-Effect Level (NOAEL) for systemic toxicity of BPA based on two multigenerational rat studies, which is 5 $mg.kg^{-1}$ $bw.day^{-1}$. This NOAEL is approximately 2000 times higher than the estimated BPA intake from FCMs for infants and a substantial 27,000 times higher for adults, as reported (Shelnutt et al. 2013). Furthermore, USEPA has established a chronic oral Reference Dose (RfD) for BPA at 50 $\mu g.kg^{-1}$ $bw.day^{-1}$.

In Canada, the Chemicals Management Plan evaluates and addresses the possible threats that chemical compounds pose to the environment. A Screening Risk Assessment Report for BPA was published in 2008. The conclusion of the report indicated that BPA might be infiltrating the environment, posing a risk to human life or health, as well as having an immediate or long-term negative impact on the environment or biological diversity. BPA was subsequently added to the List of Toxic Substances in Schedule 1 of the Canadian Environmental Protection Act, 1999 (CEPA 1999). Newborns and infants are protected from exposure to BPA by the Canada Consumer Product Safety Act. The Act makes it illegal to manufacture, import, market, or sell PC infant bottles that contain BPA. In 2010, PC baby bottles that contain BPA were forbidden. The enforcement actions of this restriction found only 1 non-compliant sample in 2011 and no non-compliant samples in 2013. As of 2014, Canadian consumers are not expected to find any liquid infant formula products packaged in BPA-containing packaging on the Canadian marketplace.

In other countries, for example, in Japan, food safety regulations are based on the Food Sanitization Law (1947) and Food Safety Basic Law (2003), which aim to protect people's health through food safety. Under Article 18 of this law, in polycarbonates, the BPA level should be $\leq$ 500 $\mu g.g^{-1}$ and $\leq$ 2.5 $\mu g.mL^{-1}$. The Ministry of Health Malaysia (MOH) has banned the importation, manufacture, or sale of any feeding bottles containing BPA since 2012 when they found the rate migration of BPA from PC bottles increased 7-fold when boiling temperature increased from 25°C to 80°C (Tsang 2011). Chinese authorities have banned

BPA in baby feeding bottles as they continue their pitched battle to improve food safety.

In India, there are currently no specific regulations governing the use of BPA in FCMs. However, its usage is regulated under various existing laws such as the Environment (Protection) Act, 1986, the Hazardous Waste (Management, Handling, and Transboundary Movement) Rules, 2016, and the Manufacture, Storage, and Import of Hazardous Chemicals Rules, 1989, due to its hazardous nature. FSSAI introduced the Food Safety and Standards (Packaging) Regulations, 2018 to regulate food contact materials and articles, including a list of packaging materials for certain categories of food and limits on the migration of heavy metals and DEHP (FSSAI 2022). The regulation of baby feeding bottles in India with regards to BPA has undergone amendments over the years, notably through the Infant Milk Substitutes, Feeding Bottles, and Infant Foods (Regulation of Production, Supply, and Distribution) Act 1992, later amended in 2003. However, despite growing concerns internationally and a draft proposal by the Bureau of Indian Standards (BIS) in 2013 aimed at restricting BPA usage in these bottles, no official publication or implementation of this draft by the Indian government has been recorded (Mahamuni & Shrinithivihahshini 2017). There appears to be a lack of specific legal measures governing the permissible levels of BPA in baby feeding bottles within the Indian regulatory framework. In contrast to numerous developed nations where well-established human biomonitoring programs for BPA exist, the involvement and exploration of public health institutions in monitoring BPA as Endocrine Disrupting Compounds (EDCs) and evaluating their health impacts on the broader Indian population have been limited or largely unexplored (Sharma et al. 2022).

The presence of regulations to restrict the usage of BPA in certain products and set maximum limits for BPA migration into food products is noteworthy. However, it is imperative to implement more stringent monitoring and enforcement measures to ensure that these regulations are being adhered to and that BPA levels in food and FCMs remain within safe limits. Rigorous monitoring can help detect any violations or non-compliance, and prompt remedial actions can be taken to prevent harmful exposure to BPA. Furthermore, it is crucial to periodically update and review these regulations based on new scientific evidence to ensure their continued effectiveness in safeguarding public health.

BPA AND ITS EFFECT ON HEALTH

BPA has recently attracted significant attention due to its identification as an EDC (Tarafdar et al. 2022). BPA is characterized as a "weakly estrogenic" substance because its binding affinity for estrogen receptors is approximately 10,000 times lower than that of natural estrogen (Im & Löffler 2016). Endocrine disruptors work by interfering with normal hormone biosynthesis, secretion, activity, or metabolism, which can adversely affect children's health, causing "altered neurodevelopment, obesity, and precocious puberty" (Braun & Hauser 2011). Several laboratory investigations and a better knowledge of the mechanisms by which BPA exerts an estrogenic effect have prompted increased attention to the harmful consequences of BPA. In animal experiments, high levels of BPA exposure during pregnancy resulted in preterm birth, reduced fetal and placental weights, slower growth, lower survival due to impairment of uterine spinal arteries, and a prolonged period for offspring to reach puberty (Ma et al. 2019). BPA exposure has also been linked to insulin resistance in animals, with the disruption of the insulin pathway obstructing glucose absorption and affecting the expression of the GLUT4 gene (Cetkovic-Cvrlje et al. 2017). BPA exposure in pregnant OF1 mice was linked to glomerular abnormalities and decreased glomerular development, implying that BPA exposure in pregnant humans may have negative consequences (Nuñez et al. 2018). Other research works have revealed relationships between prenatal or early-life BPA exposure and neurological effects, as well as the development of breast and prostate cancer in adult animals (Santoro et al. 2019). Being lipophilic, BPA can accumulate in adipose tissue, with 50 percent of breast adipose tissue containing BPA (Jain et al. 2020). Urinary BPA levels are also frequently reported to be positively associated with ovarian cancer and infertility in females (Hagobian et al. 2021). Males with higher urinary BPA concentrations displayed a significantly lower sperm count, viability, and motility (Castellini et al. 2020).

The availability of scientific papers reporting on the exposure of BPA in humans in India is limited. However, the presence of EDCs in various body fluids such as urine, blood serum, breast milk, and amniotic fluid is reported by (Shekhar et al. 2017). This study provides insights into the exposure of EDCs, including BPA, among the Indian population, highlighting the need for further research and regulatory measures to protect public health. Additionally, presence of BPA in the urine of patients has also been noted (Muthusamy et al. 2021). The study found that the mean human urine BPA concentrations were significantly higher in the patient group (5.76 ± 6.00 ng.mL^{-1}) as compared to the control group (1.18 ± 2.11 ng.mL^{-1}). These results suggest that the patients were exposed to higher levels of BPA, which could be a cause for concern. These studies highlight the need for further research to investigate the sources of BPA exposure and its potential impact on human health.

CONCLUSION

This review provides a comparative analysis of BPA sources, environmental levels, migration, and health impacts in India and other countries. Our analysis indicates that BPA is a ubiquitous environmental contaminant with a significant impact on human health. We found that in India, BPA exposure mainly occurs through the consumption of contaminated food and water, as well as occupational exposure in certain industries.

The regulatory landscape concerning BPA in FCMs, particularly in India, reflects a complex interplay between existing environmental and chemical management laws rather than specific guidelines dedicated to its usage. While various laws such as the Environment (Protection) Act, Hazardous Waste Rules, and others acknowledge the hazardous nature of BPA, the absence of stringent, specialized regulations directly addressing its permissible levels in FCMs remains apparent. The Food Safety and Standards (Packaging) Regulations of 2018 brought forth by FSSAI mark an attempt to regulate food contact materials but lack explicit provisions concerning BPA limits. Amendments to regulations governing baby feeding bottles have been proposed, yet formal implementation, as evidenced by the Bureau of Indian Standards' draft proposal in 2013, has not materialized. Notably, compared to developed nations with robust biomonitoring programs for BPA, India appears to have limited involvement from public health institutions in monitoring BPA's impact as an EDC and its broader health implications for the population. Consequently, the existing framework in India reveals a gap in tailored regulations specifically addressing BPA levels in FCMs, highlighting the need for comprehensive guidelines and active involvement of health institutions for effective monitoring and safeguarding of public health.

Our review also highlights the need for further research and regulatory measures to address BPA contamination in India and globally. India, as a rapidly developing country, needs to take proactive measures to reduce exposure to BPA and other environmental contaminants. Future research should focus on identifying the sources of BPA exposure, assessing the extent of exposure, and evaluating the effectiveness of mitigation strategies. Regulatory measures such as the banning of BPA in food-contact materials, as seen in some countries, should be considered in India as well.

In conclusion, the evidence presented in this review underscores the urgent need for action to reduce BPA exposure and mitigate its health impacts in India and globally. We hope that this review will contribute to the ongoing dialogue on environmental health and inform policy decisions to protect public health.

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